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**Field Methods to Measure Surface Displacement and
Strain with the Video Image Correlation Method
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PREFACE

This technical report was prepared by the staff of the Research Institute, The University of Alabama in Huntsville. The purpose of this report is to provide documentation of the work performed and results obtained under delivery order 86 of Marshall Space Flight Center (MSFC) Contract No. NAS8-38609. Mr. Gary A. Maddux and Mr. Charles M. Horton were Principal Investigators for this nine month level of effort. Dr. Samuel S. Russell of the Nondestructive Evaluation Branch provided technical coordination.

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official NASA position, policy, or decision unless so designated by other official documentation.

I have reviewed this report, dated 31 Mar, 1994 and the report contains no classified information.


Principal Investigator

Approval:

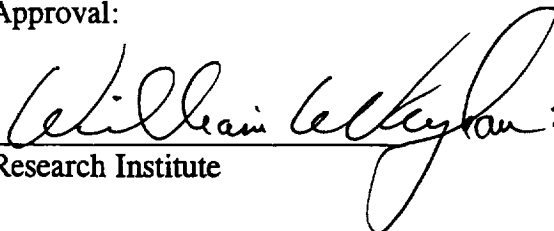
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1.0 Introduction:

The System Management and Production Laboratory at the Research Institute, the University of Alabama in Huntsville (UAH), was tasked by the Nondestructive Evaluation (NDE) Branch (EH13) at Marshall Space Flight Center (MSFC) to conduct research in the method of Video Image Correlation (VIC) for nondestructive evaluation. The goal of this research was to study methods and develop application procedures to measure the displacement and strain fields during structural testing of aerospace components using paint speckle in conjunction with VIC. The study was intended to develop the apparatus and techniques required to make VIC a useful method to measure strain and buckling of sub scale test items.

2.0 Background and Objectives:

The NDE Branch at MSFC is currently cooperating with the Polymers and Composites Branch (EH33) in an effort to more readily and accurately identify damage states in polymer fiber composites. This effort involves the utilization of a variety of techniques to determine the size and severity of impact damage in filament wound pressure vessels (FWPV) specimens. The techniques in use include electronic shearography, acoustic emissions, x-ray inspection, and ultrasonic inspection.

The method of Video Image Correlation (VIC) has undergone development in previous tasks for the NDE Branch at MSFC, and is also being applied to the inspection of the aforementioned FWPV. The NDE Branch identified a need to supplement the existing VIC software package with documentation which would make the method more accessible to those outside the development environment. The creation of such documentation required that the techniques and apparatus be studied and developed to optimize the inspection process. In order to fulfill these needs, UAH was tasked to continue the development of the VIC method and to provide a software package which would be useful in the nondestructive evaluation of a variety of material systems and components.

The objectives of this task were to develop a user's manual and an on-line Windows help system to accompany the software package. The VIC method would be applied to the NDE testing of a series of the aforementioned impact damaged graphite epoxy pressure vessels to develop application procedures. The completed software package would be suitable for distribution.

3.0 Activities:

3.1 Software Development:

3.1.1 VIC User's Manual:

A Video Image Correlation (VIC) user's manual was created. This manual explains the theory underlying the automated analysis conducted by the software as well as experimental considerations which may effect the accuracy of results. The procedures for installing and operating the software are outlined. Instructions are also included for an example which allows the user to correlate a set of supplied images and compare results with a supplied standard. The VIC user's manual is included in the appendix of this report.

3.1.2 VIC On-line Help System:

A Video Image Correlation (VIC) on-line help system was developed for use in a Microsoft Windows environment. This system is accessible by the user at any point during program operation and allows for index or search location of the desired topic. The help system is linked so as to facilitate cross referencing of related topics or may be read in a continuous manner from beginning to end. The nature and content of the help system allows the user to access information from the VIC user's manual directly on the computer screen. The source code and executable version of this software was delivered to the NASA-MSFC NDE Branch as part of the VIC package.

3.2 VIC Evaluation of Impact Damaged Graphite Epoxy Pressure Vessels

3.2.1 Overview:

VIC was used to obtain the strain and displacement fields around damage caused by blunt impacts of graphite-epoxy 5 1/4 inch ASTM test pressure vessels. Procedures for VIC application were developed during this testing. Measurements were obtained during pressure tests to failure. The VIC method maps a video image of a random paint pattern on the surface of an unpressurized bottle onto the strained image of the same pattern after applying pressure to the bottle. The image correlation mapping is achieved using an image identification algorithm. This mapping produces the displacement and strain fields with an inaccuracy of approximately 0.1% strain. The strain or displacement fields of interest were false-color plotted. The only equipment required to perform VIC inspection is a solid state B&W camera, lens, video digitization board, and a 386 or better computer. The VIC software will soon be available through NASA COSMIC.

On the 29 bottles tested broken fibers in the hoop plies were clearly indicated in the hoop strain field as areas of much higher strain at as low as 30% of expected burst pressure. The bottles tested were empty, and similar testing on 28 bottles filled with inert propellant are planned for spring of 1994. Tests of the linearity of the strain indications of damage are planned during the same proof tests. Experimental methods and scaling the strain field to model and predict incipient failure of pressure vessels will be discussed.

3.2.2 Specimens:

The filament wound pressure vessels (FWPV) evaluated here conformed to ASTM standard D2585-68 (1985). The bottles were formed by a series of helical and hoop plies, with the outermost being a hoop. All bottles contained a rubber bladder.

The population was divided into 12 groups spanning three epoxy resins and four levels of impact. All test articles utilized continuous IM7 graphite fibers. One third of the bottles were bound with each of the toughened epoxies ICI Fiberite 977-2 and 8553. The final one third contained the standard epoxy resin 3501-6. The four levels of impact were 0, 3, 5, and 7 ft. × lbf. These impacts were achieved with a 1/2 inch diameter tip on a 1 lb. mass dropped from the appropriate height.

The over spray from white and black spray paint was used to apply a speckle pattern to the surface of each bottle covering the region of impact. The randomness of each pattern allowed the images of the bottle surfaces to be more readily correlated than the uniform surface of the

unpainted bottles would have been. The painted speckle patterns resemble that shown on the test article in Figure 1.

3.2.3 Procedure:

VIC is a nondestructive evaluation technique which allows non-contact full-field displacement and strain measurement and does not require extensive isolation from common noise sources such as vibration. In many cases, the test article may be evaluated in its standard service environment.

In this case, the test bottles were pressurized internally. A typical pressurization history is shown in Figure 2. An image of the undeformed bottle was taken at 0 psig after the proof cycle. An image of the deformed bottle was taken at the first pressure hold after the proof cycle (1000 psig). For this experiment, a Sony XC-77 CCD camera with a Sigma 70-210 mm zoom lens was used to acquire images of the region of interest through a Data Translation DT-2862 video digitizing board in a PC. The stored images were then processed by the VIC software in a Windows environment.

3.2.4 Analysis:

The determination of displacement fields by the VIC software utilizes a pattern recognition algorithm. A Newton-Raphson process minimizes the overall gray-scale differences between subsets of the undeformed and deformed image. The gray-scale differences are minimized as a function of the subset's center pixel position within the deformed image. The displacement is thereby determined in row and column pixels with sub-pixel resolution. Full-field displacement measurements are acquired by correlation of one subset at a time in a grid pattern across the image. The density of the subset grid and the subset size are user definable for each set of images; thus, the automated analysis may be customized to each unique image pattern.

The VIC software may also give numbers for partial derivatives of the horizontal (v) and vertical (u) displacement components with respect to the horizontal (Y) and vertical (X) screen directions. The units of these partials are pixels-per-pixel. They may be treated as dimensionless. Partial values may be used to determine certain engineering values:

$$\begin{aligned}\epsilon_{xx} &= \partial u / \partial x = \text{linear strain in the X direction,} \\ \epsilon_{yy} &= \partial v / \partial y = \text{linear strain in the Y direction,} \\ \epsilon_{xy} &= \partial u / \partial y + \partial v / \partial x = \text{shear strain in the XY plane,} \\ \theta_{xy} &= \partial u / \partial y - \partial v / \partial x = \text{rotation in the XY plane.}\end{aligned}$$

Once the strain fields have been determined these strains may be scaled to some failure criteria by material properties. For example, the Tsai-Wu theory for laminar continuous fiber composites has been applied elsewhere. This approach relates the strains, fiber properties, and matrix properties to a maximum shear stress. The strain field may also be scaled to burst pressure. Assuming a linear projection, statistical analysis may yield a model by which strains at very low loads may be used to predict burst pressure.

3.2.5 Results:

The expected burst pressure for these bottles was 3000 psig. The results of image correlation from 0 to 1000 psig indicate regions of high strain which contrast sharply with the rest of the strain field. In Figures 3 and 4, the dark colored regions represent areas of low

strain, while the lighter colors indicate regions of higher strain. These results indicate significant damage in the bottles at their proof strength. The presence of the damage indicated by the localized regions of high strain is consistent with the low burst pressures of the two bottles and the failure mode of each.

Figure 3 indicates a chevron shaped series of high strain points. Such strain phenomenon is consistent with the subsequent growth of a chevron shaped crack in the external hoop ply in the region of interest, as shown in Figure 5. Impact damage in the form of hoop ply fiber breakage is believed to have caused fiber overloading and fiber fracture along the same plane as the matrix cracking. This bottle burst at 1288 psig, less than 43 % of expected.

More commonly, the results of image correlation indicate a smaller region of higher strain, as shown in Figure 4. A fiber break induced by the impact is believed to have overloaded the matrix, of which failure caused the entire side of the bottle to "blow out", the ensuing damage roughly centered about the point of high strain as indicated by VIC analysis. This bottle burst at 1800 psig, just 60% of expected.

4.0 Conclusion:

The Video Image Correlation (VIC) method of NDE was used to evaluate the strain fields of impact damaged graphite-epoxy pressure vessels. The procedures and techniques developed in this testing were incorporated into a user's manual and an on-line help system which supplement the VIC software package and provide procedural, analytical, and demonstrative information. The strain fields determined from FWPV testing effectively indicated impact induced fiber breaks at load levels well below failure. The success of this study indicates that Video Image Correlation is an NDE tool which should prove useful in future evaluation of damage levels in complex material systems and service components.

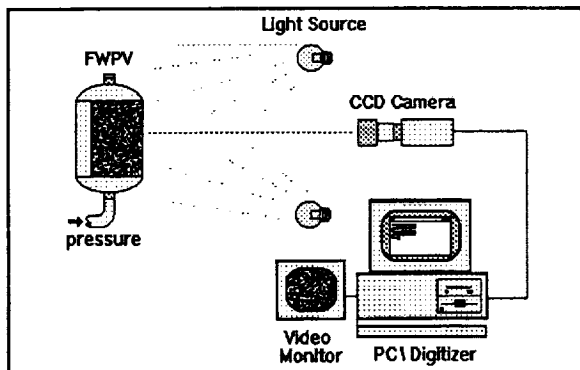


Figure 1 Data Acquisition Setup

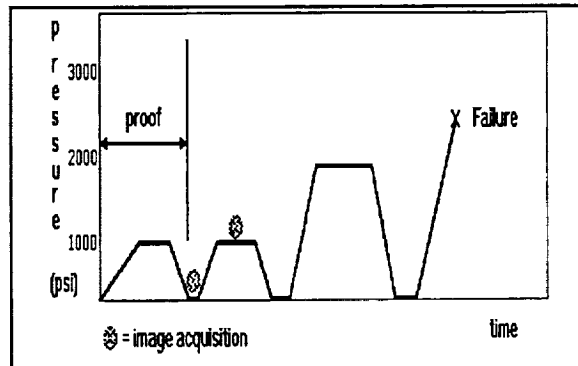


Figure 2 Typical Pressurization History

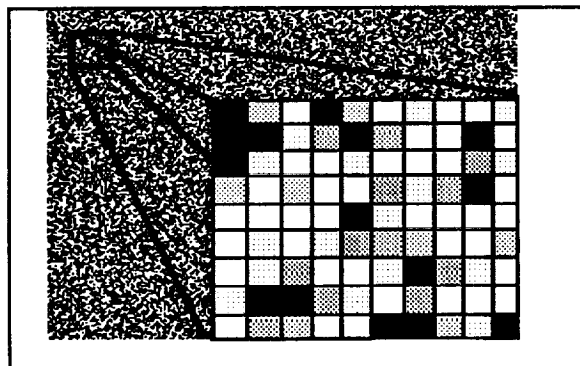


Figure 3 Speckle Image Subset

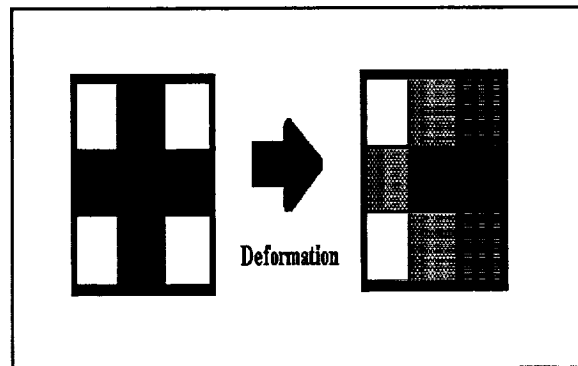


Figure 4 Subsets Indicating Deformation

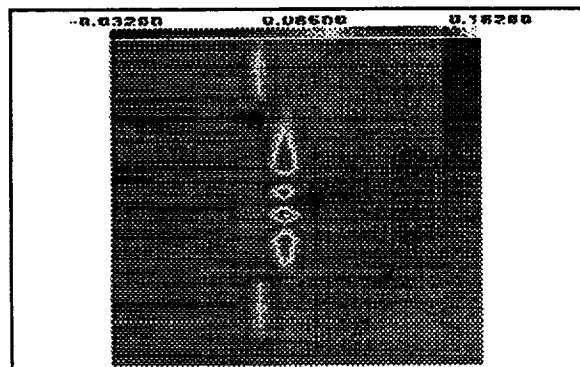


Figure 5 Bottle C123-124 Hoop Strain Field (1000 psig)

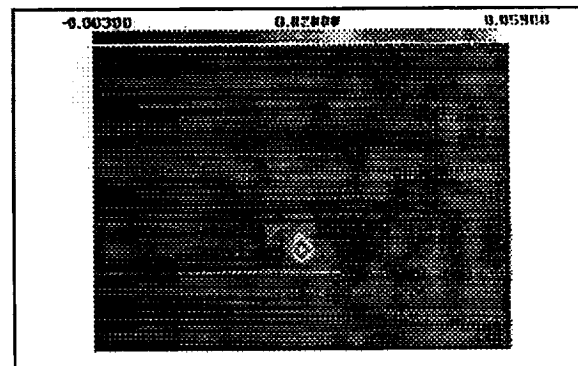


Figure 6 Bottle A001-002 Hoop Strain Field (1000 psig)

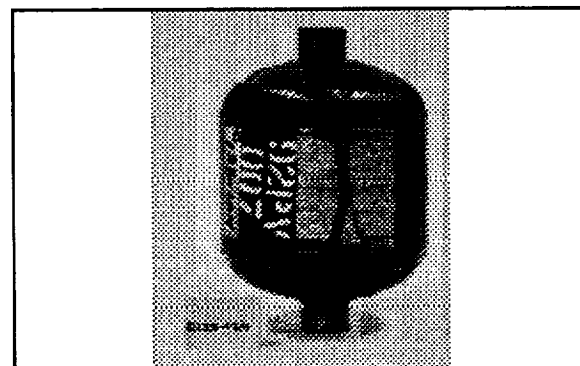


Figure 7 Failed Bottle C123-124

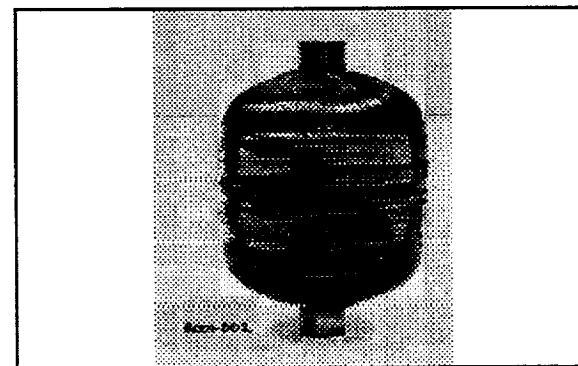


Figure 8 Failed Bottle A001-002

APPENDIX:
VIC User's Manual

**S.R. McNeill Services,
NASA Marshall Space Flight Center
Nondestructive Evaluation Branch EH13, and
University of Alabama in Huntsville Research Institute**

Manual for 2-D Sub-Pixel Digital Video Image Correlation

Version 9/16/93

Stephen R. McNeill

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1. Introduction

1.1 The VIC Manual

This manual contains useful information on the following: the experimental method, the mathematical basis for the software, and program use. Throughout this manual, the following conventions will be used to denote special items within the text:

- FILE NAMES will be denoted as: **FILENAME.EXT**
- WINDOW MENU ITEMS will be denoted as: **Option**
- REFERENCES TO OTHER
 SECTIONS OF THE TEXT will be denoted as: *Other Section.*

For assistance during software run time, refer to the on-line Help system. If assistance is required which is not addressed in this manual or the on-line Help system, contact Steve McNeill at (803) 777-3407.

1.2 Introduction to VIC

Sub-pixel digital **Video Image Correlation (VIC)** is an experimental technique that can be used to determine the deformation of objects subject to loadings. The technique requires that digital images be obtained of the object before and after deformation. Also, the object being imaged must have a characteristic pattern on its surface. This pattern may be naturally occurring or applied by the experimentalist. The technique presented here is for two dimensional correlation; that is, the deformation of the object is restricted to motion parallel to the plane of the camera image sensor.

1.3 Theory

Digital images may be obtained from many different sources and be presented in different formats. Typically, the images may be acquired by a solid state video camera whose signal has been digitized using a video digitizer. Commonly, the format will be a set of numbers of size 512 by 512, each of which is 8-bits in length. This is true for a video camera with a 512 by 512 sensor array and an eight bit video digitizer. Each number is representative of the light intensity reaching an area on the image sensor. The area of the sensor represented by this value is referred to as a picture element, or pixel. The value of the light intensity is referred to as the gray-level. The gray level values range from 0 to 255. Typically 0 represents black, 255 represents white, and the numbers between are linearly related to the shades of gray. These gray levels are

linear between black and white. Various sizes of images can currently be used, but as presently formatted, only 8-bit gray level images can be analyzed.

The concept of video image correlation is based upon a computer algorithm to locate small regions of a random pattern after the pattern deforms. These small regions, illustrated in **Figure 1**, are referred to as *subsets*. This deformation may be due to mechanical straining or rigid body motion. Determination of the motion field between two digital images of the same surface requires partitioning one image into pixel subsets, usually the undeformed image, and finding the corresponding region in the other image, usually the deformed image. This requires that each subset have a unique pattern. **Figure 2** illustrates the relationship between a pixel subset containing a black cross on a white field before and after a rigid body translation to the right of one pixel.

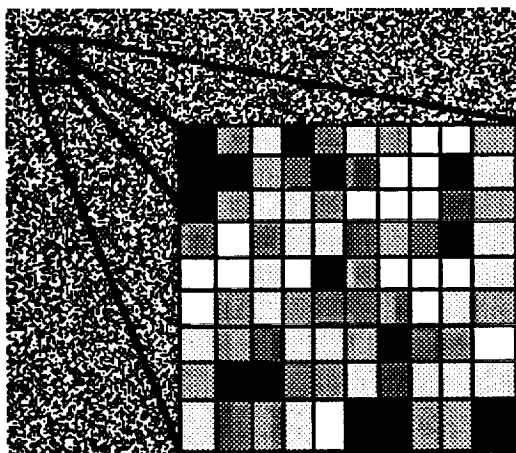


Figure 1. Digitized Image Subset of a Random Pattern

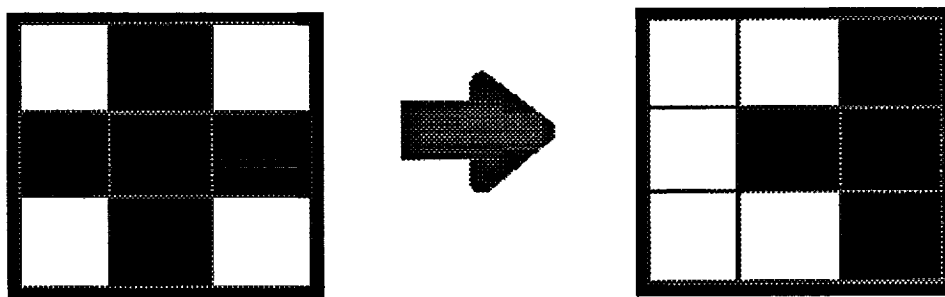


Figure 2. Deformed Pixel Subset Pattern

Each subset must be large enough to include sufficient character to appear unique or the program will not be able to distinguish one subset from another. If this occurs, the error in the deformation field will be large or the program will fail. Utilization of larger subsets or a pattern with more character will improve the correlation.

The pattern may be naturally occurring or applied to the object. An example of natural occurring patterns that have been used with this technique are the grains and grain boundaries seen when studying the microstructure of metals. Another example is solid-rocket propellant which has fine particles dispersed in a matrix material.

Frequently a pattern must be applied to the surface. Some of the techniques for applying the patterns include the dusting of the surface with fine particles, over-spray from black and white spray paint, or the application of phosphorescent particles. The application of the pattern is only limited by the imagination of the experimentalist. A random pattern which is suitable for correlation is shown in Figure 3.

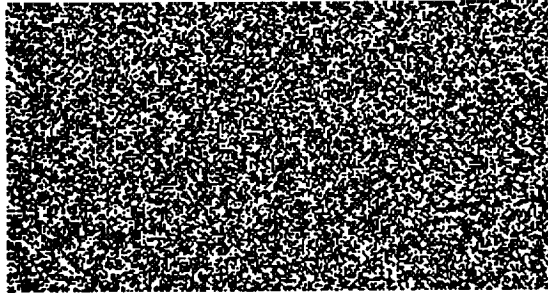


Figure 3. Typical Random Pattern Suitable for Correlation

1.4 Coordinate System and Measurements

The X and Y directions are shown in Figure 4. These correspond to video screen coordinates measured in pixels for a (480 x 512) image. The row in which a pixel lies is its X coordinate, and the column in which it lies is its Y coordinate. The results from this program will be displacement components U, in the X direction, and V, in the Y direction. These displacements are measured in units of pixels.

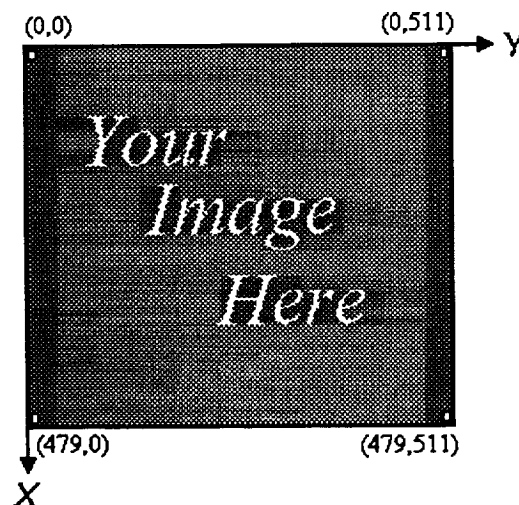


Figure 4. VIC coordinate system.

The program may also give numbers for partial derivatives of these two displacement components with respect to each direction. The units of these partials are pixels-per-pixel. They may be treated as dimensionless. Partial values may be used to determine certain engineering values:

$$\partial U / \partial x = \epsilon_{xx} = \text{linear strain in the X direction,}$$

$$\partial V / \partial y = \epsilon_{yy} = \text{linear strain in the Y direction,}$$

$$\partial U/\partial y + \partial V/\partial x = \gamma_{xy} = \text{shear strain in the XY plane,}$$

$$\partial U/\partial y - \partial V/\partial x = \theta_{xy} = \text{rotation in the XY plane.}$$

1.5 Image Quality

The results obtained from this program will only be as good as the digital images supplied. The pattern on the surface greatly influences the quality of the correlation. The pattern must have a unique sub-pattern for each possible subset. A rule of thumb is that each subset should appear to have at least three distinct dark regions in it and the sum of these dark regions should cover about 50% of the subset area. These are rough estimations and almost any pattern can be correlated if care is taken.

The object must be restricted to minimal movement towards the camera recording the images between the acquisition of the two images to be correlated, because the analysis upon which the software algorithm was formulated assumes all movement of the object is parallel to the image sensor. Detectable movements toward the camera will be interpreted by the program as straining of the object radially from the optical center. For experiments where out of plane motion can not be avoided there are some methods which can be used to negate the effects of this motion.

Mathematically subtracting out the effects of out of plane motion or using a longer focal length camera lens can minimize detrimental effect. The user must understand the nature of the object and loading being studied, and determine if this technique can be used to obtain the information desired. If out-of-plane motion or deformation can not be compensated for by a mathematical or experimental correction, then a 3-D correlation technique will need to be used. Information on this can be obtained from Steve McNeill at (803) 777-3407.

When appropriate images are correlated an error in the displacements of ± 0.02 pixels can be expected. These errors rise from the electronics in the camera and the video digitizer. The 0.02 pixel error is typical when using a standard CCD video camera, such as a Sony XC-37, and mid-priced digitizer, such as a Data Translation DT2862. If the pattern is poor or there is significant noise in the electronics then the error will be higher.

The technique is also capable of giving numbers representing the displacement gradients of an object, including normal strains. Again, the error is a function of pattern, electronics, and also of the subset size. **For subsets of size 20 pixels by 20 pixels the error in the strains may be as large as several percent strain.** Error of this magnitude may make the strains unrealistic, although calculating them during the correlation process decreases the error of the displacements. Using larger subsets results in higher accuracy in the calculated displacement gradients. This is a process of approximation and the results may require interpretation.

1.6 Imaging Technique

As explained in the section *Image Quality*, this technique is only applicable when motion parallel to the camera sensor dominates any out of plane motion. **This is a 2D technique.** Typically, the test specimen will be approximately flat, and all surface strains will be predominantly planar. The camera should be positioned such that the sensor grid is parallel to the specimen surface. Furthermore, any error caused by out of plane motions will be approximately proportional in magnitude to the amount of displacement towards or away from the sensor grid divided by the original distance from the specimen to the sensor grid. Thus, to minimize error due to out of plane motion, the camera should be placed a considerable distance from the specimen, and a telephoto lens should be used.

Proper illumination of the specimen is important. The analysis upon which the software algorithm was based utilizes a pin-hole camera model. To most closely approximate this model, the camera aperture should be almost closed, which requires large amounts of light to properly illuminate the specimen. The lighting used should be carefully arranged such that the specimen is illuminated thoroughly and uniformly. Any glare, shadows, or reflections should be eliminated before attempting to capture images for data.

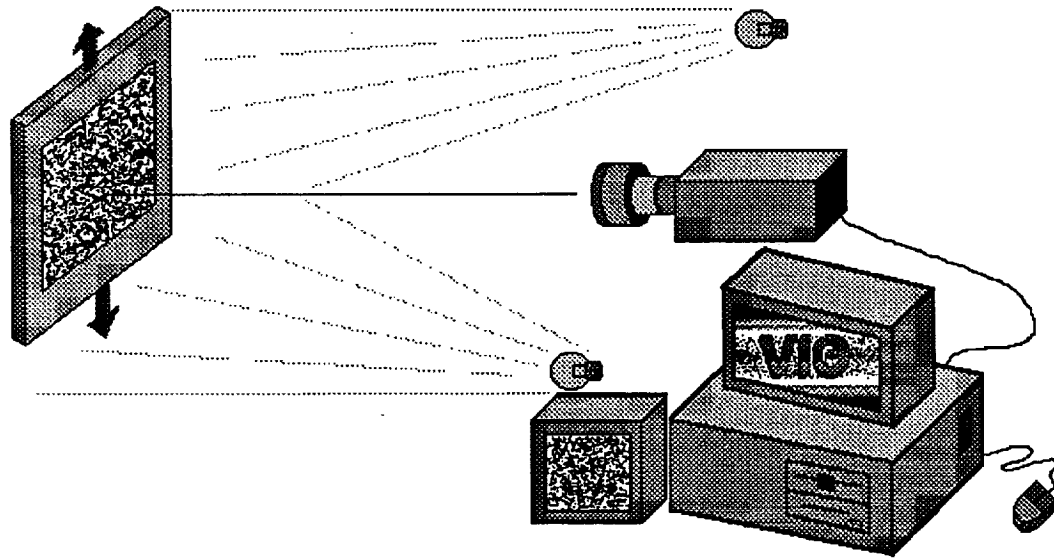


Figure 5. Hardware Setup

2. Getting Started

2.1 Computer Requirements

An IBM PC compatible computer running Microsoft Windows 3.1 in the enhanced mode is required. This will require a 386 or better processor and 2 MB or more of RAM. While running, the program can require as much as 3.5 MB of memory storage. Although the program will run on a computer with as little as 2 MB RAM, Windows must be set up to have a swap space of at least 5 MB. The size of the required Windows swap space is dependent on the amount of computer RAM and the number of concurrent times the correlation program is being run, as well as any other application that the user may have running. The operator should consult the Windows manual for setting up Windows in the enhanced mode and setting up the swap space. Usually the program is run on a 386-25 MHz PC compatible with 4 MB of RAM and a 20 MB swap space or better. Significant improvement in speed occurs when running on a 486-50 MHz or -66 MHz PC compatible with 8 MB RAM and 32 MB swap space.

2.2 Installing the Program

A single diskette houses the VIC program. At the DOS prompt `A:\>` type `INSTALL`. The VIC software will create the directories `C:\VIC`, `C:\VIC\HELP`, and `C:\VIC\EXAMPLE`. The VIC software and example files will be automatically installed in these directories. VIC must then be setup as a Windows program item in the Program Manager.

- If you wish to create a new program group for VIC select **File**, then **New**. Select **Program Group**, then click on **OK**. Click on the **Description** box and type **VIC**. Click on the **Group File** box and type `C:\VIC\VIC.GRP`. Select **OK**. Windows will create a VIC window in the Program Manager.

Click inside the new VIC window. Select **File**, then **New**. Select **Program Item**, then click on **OK**. Click on the **Description** box and type **VIC**. Click on the **Command Line** box and type `C:\VIC\VIC.EXE`. Click on the **Working Directory** box and type `C:\VIC`. Windows will create the program item **VIC** in the VIC program group.

- If you wish to add VIC to an existing program group, click on an icon in that program group. Then continue with the second step in the procedure above.



The icon for the VIC program item is set by Windows to a default application icon. An custom VIC icon, shown at the beginning of this paragraph, is included. To

use the VIC icon, click on the one Windows created. Select **File**, then **Properties**. Select **Change Icon**. Windows will reply that you may select one from its collection. Click on **OK**, then **Browse**. Select the root directory **C:**. Select the **VIC** subdirectory. Select **VIC.ICO**. Select **OK** on the Browse window. Select **OK** on the Change Icon window. Select **OK** on the Properties Window.

2.3 Starting the Program

The program is started by either double clicking on the icon that was created when it was installed or by opening the Windows File Manager and double clicking on the **VIC.EXE** file. Once this is done, the program will begin to run. A window will appear with the header **Sub-Pixel Digital Image Correlation**. This is the correlation program where all options and input/output entries will be made. Also, this is a standard window with all standard Windows sizing and positioning operations available. The associated windows have several options on the option bar which allow different operations and configuration to be run. These options and their sub-options will be described in the next section.

3. Program Menus

3.1 Help Menu

The Help Menu presents options which allow the user access to information about the program copyright and version, as well as the on-line help system. This menu may be accessed by clicking on **Help** on the main window header bar. Clicking on one of this menu's options will select that option.

About: Select the **About** option by clicking on it to display the standard Windows "About Box". For this program, the box will contain the copyright and version information.

Help: Selecting the **Help** option will cause the program to activate the on-line help system. Click on **Help** for the main Help menu. The main index of the help system offers the options listed below.

- **Help:** This option presents help with the structure and operation of the Help system.
- **Image Correlation:** This option presents help with the options on the Image Correlation Menu from the main window header bar. The Image Correlation menu presents options which allow the user to direct the correlation analysis of images and tailor that process to each set of images. Help for this menu may be accessed by clicking on **Image Correlation** on the main Help menu.
- **Display:** This option presents help with the options on the Display Menu from the main window header bar. The Display Menu presents options which allow the user to graphically display images, correlation results, and other information on the computer monitor. Help for this menu may be accessed by clicking on **Display** on the main Help menu.
- **Image Type:** This option presents help with the options on the Image Type Menu from the main window header bar. The Image Type options are included to facilitate the use of various image formats. For the correlation program to work properly, the program must have knowledge of how the image data is stored. Help for this menu may be accessed by clicking on **Image Type** on the main Help menu.
- **General:** This option presents general help with the VIC system, including experimental setup and the theory upon which the software algorithms were developed. This help option may be accessed by clicking on **General** on the main Help menu.

- **VIC Example:** This option details an example VIC session analyzing images supplied with the VIC system. The user may compare the results with a supplied set to assure the system is being used properly.

3.2 Image Correlation Menu

The Image Correlation Menu presents options which allow the user to direct the correlation analysis of images and tailor that process to each set of images. This menu may be accessed by clicking on **Image Correlation** on the main window header bar. Clicking on one of this menu's options will select that option.

Technique: This is used to select the type of analysis that will be performed. The techniques available include the Coarse-Fine Search and the Newton-Raphson methods. See the *Image Correlation Technique* section for more details on the methods. The technique selection when not available will be grayed. This will occur when correlation is being performed.

- **Coarse-Fine:** This sub-option allows one to select the coarse-fine technique to be used when correlation is performed. When selected, a check mark will appear next to this sub-option. To select **Coarse-Fine** search one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu containing **Technique**. Place the cursor on **Technique**, click once, and a new sub-menu will appear containing **Coarse-Fine Search**. Move the cursor until it is highlighted and click the mouse once.
- **Newton-Raphson:** This option allows one to select the Newton-Raphson technique to be used with correlation. Once selected, a check mark will appear next to this sub-option. To select **Newton-Raphson**, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu containing **Technique**. Place the cursor on **Technique**, click once, and a new sub-menu will appear containing **Newton-Raphson**. Move the cursor until it is highlighted and click the mouse once.
- **NO-Interpolation Factors:** This option is useful for fewer than ten subset points. The program requires bilinear interpolation to determine sub-pixel displacements. Selecting this option causes the program to calculate each interpolation factor only as needed, saving time and memory. For more than 10 points, this option should not be selected, and the program will pre-calculate all interpolation factors. This option will slow the program down considerably with redundant calculations if it is selected for more than 10 data points.

To select **NO-Interpolation Factors**, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu containing **Technique**. Place the cursor on **Technique**, click once, and a new sub-menu will appear containing **NO-Interpolation Factors**. Move the cursor until it is highlighted and click the mouse once.
- **Newton-Raphson with LM:** Not available at the time of this writing. This option will allow one to select a hybrid correlation technique involving Newton-Raphson and Levenburg-Marquardt methods. This technique utilizes a

multiplication factor on Newton Raphson slopes, and promises higher speed and stability.

To select **Newton-Raphson with LM**, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu containing **Technique**. Place the cursor on **Technique**, click once, and a new sub-menu will appear containing **Newton-Raphson with LM**. Move the cursor until it is highlighted and click the mouse once.

Search Method: The method by which correlation points are selected is chosen from this option. When large number of points need to be correlated, typically the Grid method will be selected. This will automatically select points to be correlated according to the parameters that can be set using the Select command, described below. The Point method of selecting points is by moving the mouse until the cursor is at the desired position on the displayed image and clicking once, starting correlation for that point. The File search method allows the user to specify multiple correlation points, by their screen coordinates, in a file which the program will read. The **Search Method** option will be grayed when not available, during correlation.

- **Grid:** The Grid search method is chosen from this option. The Grid Search Method is illustrated in Figure 6. When selected, a check will be displayed next to this sub-option. To select Grid Search, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu which will contain **Search Method**. Place the cursor here and click once. A new sub-menu will appear containing **Grid**. Move the cursor until it is highlighted and click the mouse once.

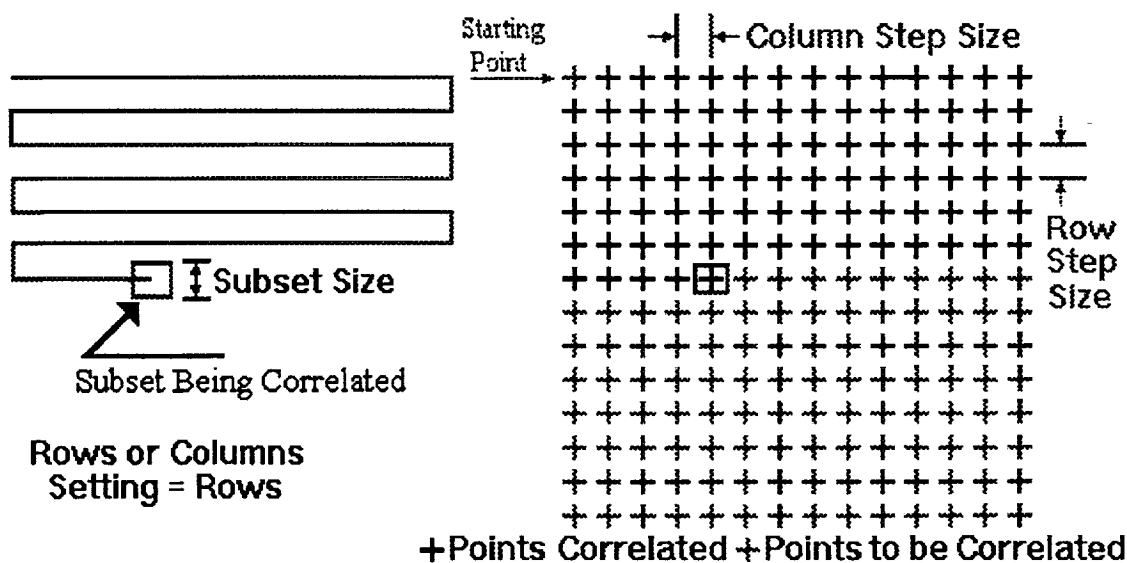


Figure 6. Grid Search Method

- **Point:** The Point search method is chosen from this option. When selected, a check will be displayed next to this sub-option. To select Point Search, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu which will contain **Search Method**. Place the cursor here and

click once. A new sub-menu will appear containing **Point**. Move the cursor until it is highlighted and click the mouse once.

- **File:** The File search method is chosen from this option. When selected, a check will be displayed next to this sub-option. To select File Search, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu which will contain **Search Method**. Place the cursor here and click once. A new sub-menu will appear containing **File**. Move the cursor until it is highlighted and click the mouse once.

Correlation Measure: This option allows the user to select which method will be used to determine how well the points have been correlated. **Figure 7** illustrates the relationship between a pixel subset containing a black cross on a white field before and after a rigid body translation to the right of 3/4 pixel. Because the camera sensor is a segmented array and the deformation of the object will rarely occur in increments corresponding to the dimensions of the sensor pixels, the deformed pattern can not be expected to match the original gray levels exactly. Although the VIC program may determine a correct 3/4 pixel movement, the correlation factor will be greater than zero, indicating a difference in the gray levels of the two subsets. The higher the correlation factor, the greater the difference between gray level patterns.

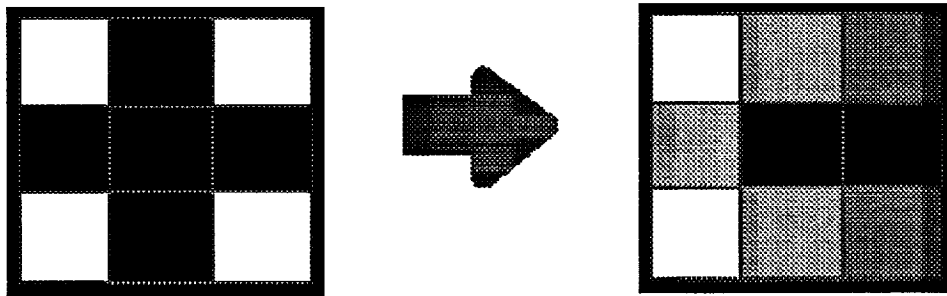


Figure 7. Subpixel Subset Deformation

The two available methods for reporting correlation factors are detailed below. The Least-Square method is generally preferred for its speed, but the Cross Correlation method may be worth waiting for in some instances.

- **Least Squares:** When this option is selected, the program will determine how well the subsets have been correlated by the sum of the squares of the differences between the subset gray levels. This Correlation Factor will be minimized to find the best solution. Large subsets will inherently cause higher Least Squares Correlation Factors than small ones will. For this reason, there is no absolute "good" and "bad" range of Least Squares Correlation Factors. For example, a Correlation Factor of 10 may be acceptable for a subset size of 40 but not for a subset size of 20.

To select Least Squares Correlation Measure, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu which will contain **Correlation Measure**. Place the cursor here and click once. A new

sub-menu will appear containing **Least Squares**. Move the cursor until it is highlighted and click the mouse once.

- **Cross Correlation:** When this option is selected, the program will use a normalization technique to determine how well subsets have been correlated. Independent of subset size, the Cross Correlation Factor will always exist between 0 and 1, where 0 is a perfect correlation, 1 is no correlation, and the values between vary linearly with the degree of correlation. NOTE: The Cross Correlation Factor is not utilized for optimization in the numerical analyses. The Cross Correlation Factor is calculated after the Least Squares Correlation Factor has been minimized, and is calculated for means of reporting only.

To select Cross Correlation Correlation Measure, one must first place the cursor on the **Image Correlation** option and click the mouse once, bringing up a menu which will contain **Correlation Measure**. Place the cursor here and click once. A new sub-menu will appear containing **Cross Correlation**. Move the cursor until it is highlighted and click the mouse once.

Go: The **Go** command will begin the correlation process which will use **Image Type** and **Settings** data. The user will be prompted for the undeformed image, deformed image, and output data file names. See *Entering File Names* section for information on how to enter file names. Once **Go** is selected, it will be replaced with **Stop**.

To select **Go**, one must first place the cursor on the **Image Correlation** option and click the mouse once. This will bring up a menu which will contain **Go**. Place the cursor here and click once.

Stop: This command will stop the correlation process. Once stopped, the user can restart the process after changing system parameters. The **Stop** command will only appear if correlation is running. After **Stop** is selected it will be replaced with **Go**. **Stop** may be selected in the same manner as **Go**.

Settings: Correlation points, the time between correlation passes, and initial search displacements are selected through this option. This option will be grayed and unavailable during correlation. For more information on selecting **Settings** values, see the *Settings Values* section. For more information on entering data when **Settings** has been selected, see *Entering Settings Data* section.

New Image: This is used to restart the correlation using new images. It is grayed and unavailable until **Go** and **Stop** have been selected. Selecting this option will restart the correlation process after prompting the user for undeformed image, deformed image, and output data file names.

To select **New Image**, one must first place the cursor on the **Image Correlation** option and click the mouse once. This will bring up a menu which will contain **New Image**. Place the cursor here and click once. The user will then be prompted for new file names. Correlation will then restart with the new images. See *Entering File Names* section for information on how to enter file names.

3.3 Display Menu

The Display Menu presents options which allow the user to graphically display images, correlation results, and other information on the computer monitor. This menu may be accessed by clicking on **Display** on the main window header bar. Clicking on one of this menu's options will select that option.

Image: This option may be selected to start the image display process. The image of the type selected will be read from an image file and a bit-map for display will be created. Once the bit-map is complete, the image will be displayed in the window. Some parts of the image may not be seen if the window is not large enough to display it. The appearance of the image will depend on the graphics mode of the PC. For modes with 256 colors, the image will look almost identical to the image as seen by the camera.

If a camera with non-square pixels is used, then there will be some distortion in either the horizontal or vertical direction. This will lead to effects like a circle being displayed as an ellipse or a square becoming a rectangle. If the PC is in a 16 color mode, then the image will be displayed only using 4 shades of gray. This may lead to a display that does not resemble the original image. Images should be displayed using the highest number of colors possible.

If a video monitor is being used in line with the camera for viewing live and digitized images, then the image displayed by the correlation program may not appear to be as bright or clear as that on the video monitor. The appearance of the image on the video monitor may be altered by adjusting the color, contrast, and brightness controls. These settings are constant for the computer display, and may be different than those on the video monitor.

B/W Bars: The appearance of a gray level image is adjusted through this option using a computer generated pattern of vertical black and white bars. The darkest bar will be on the left and the lightest on the right. The program will try to display 256 bars each with a different shade of gray. The graphics mode being used determines the appearance of these bars.

Zoom Out: This option presents a global view of images that are too big to display on the monitor. The program will display the bit map with every other row and column removed. This will give an image which can be displayed in most windows and still be recognizable. This is a temporary viewing which is removed using one of the Shift-options described below.

Grid: This option displays the original data points as a grid exaggerating all deformations for a clear picture of the overall deformation as shown in **Figure 8**. The program will prompt the user for the name of the data file in which the results may be found. See *Entering File Names* section for information on how to enter file names.

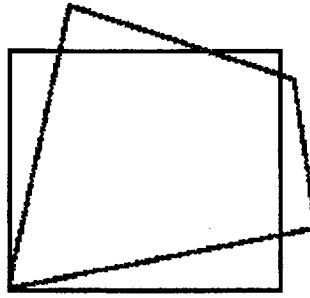


Figure 8. Grid Display

Colors: This option allows the user to graphically display the results of correlation. The program displays the results topographically, with contour lines represented by bands of different colors. The scale magnitudes appear directly above the results. The user may select to display any of the following results by clicking on that option:

$$U, V, \partial U / \partial x, \partial U / \partial y, \partial U / \partial x, \partial U / \partial y$$

The program will then prompt the user for the name of the data file in which those results may be found. See *Entering File Names* section for information on how to enter file names.

Save Screen: This option saves the displayed image as a bit map file, which may be printed or transferred into a graphics operation program such as MS Windows PaintBrush.

3.4 Image Type Menu

The Image Type options facilitate the use of various image formats. For the correlation program to work properly, the program must have knowledge of how the image data is stored. The program allows the user to select from several included image types and others are available or can be created (Contact Steve McNeill at (803) 777-3407 for more information). The different image types and their formats for the sub-options follow.

Select an image type by moving the cursor to the **Image Type** menu and clicking the mouse once. A sub-menu will appear with the different types available. To select an image type, move the mouse until the desired image type is highlighted and click the mouse. The image type currently selected will be checked. If an image type is not available or other operations are being performed, which must have a consistent image type until their completion, the image typed will be grayed. A grayed image type is not available for selection and clicking on it will not perform any operation.

SRM's Data Translation: This is for images obtained by Steve McNeill's Data Translation Driver program. The image format for this type is as follows: The 8 bit gray level for each pixel is stored in binary, sequentially starting with the upper left pixel and moving across the image to the right 512 pixels. After the first row is stored,

then the next row is stored in the same manner until 512 rows are stored. The image file will contain 262,144 bytes.

SRM's 480's: The format for this type is the same as the **SRM's Data Translation** format except there are only 480 rows. The file will contain 245,760 bytes.

SRM's Matrox: This is for images obtained by Steve McNeill's Matrox Driver program. The image format for this type is as follows: The 8 bit gray level for each pixel is stored in binary, sequentially starting with the upper left pixel and moving across the image to the right 512 pixels. After the first row is stored, then the next row is stored in the same manner until 512 rows are stored. The image file will contain 262,140 bytes.

MSFC Microscope: This is for images obtained from the image processing system located at NASA-MSFC. The system is located in Building 4711. The format for this image is the 8 bit gray level value is stored starting with the upper-left-most pixel. The first 256 pixels are stored and then the next line's 256 pixels are stored. This continues until the first 256 rows are stored. Then the 257th through 512th pixels of the first row are stored. This continues until the 256th row. The 1st through 256th pixels for rows 257 through 480 are stored. The 257th through 512th pixels are stored for rows 257 through 480.

MSFC-CT: This is for images obtained from the NASA-MSFC ACTIS system. The images are read from the ACTIS system tapes by a program on the Micro-VAX. The format for these images is such that each pixel is 2 bytes and is stored starting with the upper-left-most pixel and stored in sequential order moving left to right for 1024 pixels. This repeats for all 1024 lines of the ACTIS image. As of this writing, CT images can not be used for correlation and this selection exists only to allow the display of CT images.

SRM's Videk-1024: This is for images obtained by Steve McNeill's Videk Driver program. The image format for this type is as follows: The 8 bit gray level for each pixel is stored in binary, sequentially starting with the upper left pixel and moving across the image to the right 1024 pixels. After the first row is stored, then the next row is stored in the same manner until 1024 rows are stored. The image file will contain 1,048,576 bytes, which is 1 MB.

TIF (some): A limited TIF file reader has been included and should be used with caution.

4. Program Use

4.1 Entering File Names

At several stages during the running of the program the user will be asked for a file name. Typically, these names are for the image file or occasionally an output data file. Irrespective of file type the window for entering these names will look and operate the same.

When the program prompts the user for a file name a new active window, shown in **Figure 9** will appear on the screen. It has five parts which are:

- 1) the File Name Entry Box,
- 2) current default path,
- 3) the List Box which will contain a listing of files in the current directory with the pattern specified in the file name entry box,
- 4) an Open button, and
- 5) a Cancel button.

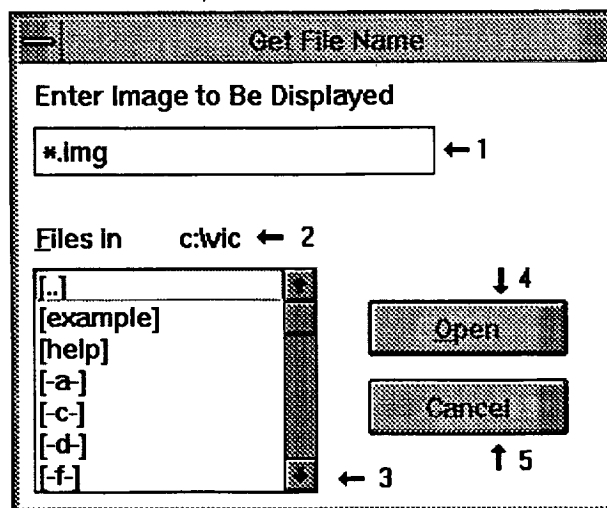


Figure 9. File Name Window

The File Name Entry Box is used to enter the name of the desired file. Enter the file name by either the keyboard or by using the mouse to select from the List Box. When the File Entry Box first appears, the default name in the box is highlighted. If any keyboard entry is made at this time then all the letters in the highlighted area will be removed and replaced with the keyboard entry. If only part of the name is to be changed, then the user should move the cursor with the mouse. While depressing the

left mouse button, place the cursor where the changes are to begin. Use the mouse to highlight the area of change by dragging the cursor. Release the left button when the end of the string to be changed has been reached. Now, any entry from the keyboard will replace the highlighted area.

Another way to enter names in the file name box is to select the desired file from the File List Box. Use the mouse to move the cursor to the desired file and click once. The name of that file will appear in the File Name Entry Box. The files displayed in the List Box will be dependent on the pattern in the File Name Entry Box. That is, if in the File Name Entry Box appears *.IMG then only files with an extension of .IMG will appear in the List Box. To have all files displayed, *.* should appear in the File Name Entry Box.

The files listed in the list box exist in the current default directory displayed above the list box. To change the default directory, the user will highlight one of the directories displayed in the list box and click once. The list box will show all subdirectories below the default by enclosing them in square brackets, []. The list box will also show each available disk drive, and one that is [..]. To get to a different subdirectory, highlight that subdirectory and click once. Use the same procedure to change disk drives. To move up in the subdirectory tree highlight the [..] line and click once. Doing any one of these will update the list box with the entries with the file name box's pattern in the new default directory.

After entering the file name into the entry box, accept the file name by moving the cursor to the Go button and clicking once. This process can be eliminated by double clicking on a valid list box entry. If the user can not find the desired file or decides not to continue, then the cancel button allows termination of the file name request process.

4.2 Settings Values

Settings controls the search pattern, subset size, initial guesses for displacements, and time between passes. When Grid Search Method is selected, points to be correlated will be selected according to a serpentine pattern which will start at a point determined by the data in the start row and start column data boxes. After the first point is correlated, the location of the second point will be determined by the values in the Row Step Size, Column Step Size, and Row/Column data boxes. If in the Row/Column box is an r or R, then the second point will be at the image point which is at the same row as the first point and its column will be the First Column data box value plus the Column Step Size data box value. Following values will continue in this manner until the current column plus the Column Step Size exceeds the Last Column box value. Additional points on that row will be selected by subtracting from the previous column value. The path produced is shown in Figure 5.

- **Subset Size:** The subsets to be correlated will contain the same number of rows and columns of pixels. The Subset Size is the number of pixels on each side of the subset. A typical value for this is 20, but this is pattern dependent. Remember that subsets must be large enough to include sufficient character to appear unique, but larger subsets will inherently have larger Correlation Factors if Least Squares

Correlation Measure is selected. The Subset Size should be the smallest possible value such that each subset correlated will have several dark and light spots. If the subset size is chosen such that no characteristic pattern is in the subset, then the results obtained will be meaningless. Choose the subset size with care.

- **First Row:** This is the row at the center of the first subset to be correlated, measured on the undeformed image, if **Grid Search Method** is selected. Note that there will be subset pixels, equal in number to half the Subset Size, above this value. As these subset pixels will be correlated from the undeformed image to the deformed image, care must be taken to assure that before and after deformation neither subset contains pixels that are off the top of the image or extend beyond specimen edges. All subset pixels before and after deformation must exist on the specimen's surface within the extents of the image.
- **Last Row:** This is the row at the center of the last subset to be correlated, measured on the undeformed image, if **Grid Search Method** is selected. Note that there will be subset pixels, equal in number to half the Subset Size, below this value. As these subset pixels will be correlated from the undeformed image to the deformed image, care must be taken to assure that before and after deformation neither subset contains pixels that are off the bottom of the image or extend beyond specimen edges. All subset pixels before and after deformation must exist on the specimen's surface within the extents of the image.
- **Row Step Size:** If **Grid Search Method** is selected, then the centers of correlated subsets will be separated vertically by this number of pixels on the undeformed image.
- **First Column:** This is the column at the center of the first subset to be correlated, measured on the undeformed image, if **Grid Search Method** is selected. Note that there will be subset pixels, equal in number to half the Subset Size, to the left of this value. As these subset pixels will be correlated from the undeformed image to the deformed image, care must be taken to assure that before and after deformation neither subset contains pixels that are off the side of the image or extend beyond specimen edges. All subset pixels before and after deformation must exist on the specimen's surface within the extents of the image.
- **Last Column:** This is the column at the center of the last subset to be correlated, measured on the undeformed image, if **Grid Search Method** is selected. Note that there will be subset pixels, equal in number to half the Subset Size, to the right of this value. As these subset pixels will be correlated from the undeformed image to the deformed image, care must be taken to assure that before and after deformation neither subset contains pixels that are off the side of the image or extend beyond specimen edges. All subset pixels before and after deformation must exist on the specimen's surface within the extents of the image.
- **Column Step Size:** If **Grid Search Method** is selected, then the centers of correlated subsets will be separated horizontally by this number of pixels on the undeformed image.
- **Rows or Columns:** The correlation will run through the correlation subsets on a serpentine path.

If **Rows** is selected, then the path will begin stepping across the First Row from the First Column to the Last Column at intervals of Column Step Size. At the end of the First Row, the path will move to the row equal to the First Row plus the Row Step Size within the Last Column. The path will then cross that row from the Last Column to the First Column. This process will continue until the Last Row has been correlated. Set this value to **r** or **R** to select Rows.

If **Columns** is selected, then the path will begin stepping down the First Column from the First Row to the Last Row at intervals of Row Step Size. At the end of the First Column, the path will move to the column equal to the First Column plus the Column Step Size within the Last Row. The path will then cross that column from the Last Row to the First Row. This process continues until the Last Column has been correlated. Set this value to **c** or **C** to select Columns.

- **Initial V Displacement:** This value is an initial guess for V displacement used to start the correlation. Estimate this value as near as possible to the point with coordinates (First Row, First Column).

Display both the deformed and undeformed images. Click on the undeformed image. Locate a recognizable feature near the desired point on this image. Move the mouse such that the cursor points to that feature. Record the Row and Column of the undeformed point. Click on the deformed image. Move the mouse such that the cursor points to the same feature on the deformed image as it did on the undeformed image. Record the Row and Column of the deformed point. The **Initial V Displacement** value is the deformed column value minus the undeformed column value.

The guess does not have to be exact but must be "close" to the correct value. The definition of close will vary with technique chosen and subset size. For the **Coarse-Fine** search method, typically ± 10 pixels is adequate. For the **Newton-Raphson** method, anything greater than ± 3 pixels may have trouble. After the first point is correlated, other points will automatically be given a guess based on previous values.

- **Initial U Displacement:** This value is an initial guess for U displacement used to start the correlation. Estimate this value as near as possible to the point with coordinates (First Row, First Column), in the same manner as the **Initial V Displacement** value. The **Initial U Displacement** value is the deformed row value minus the undeformed row value.
- **Time Between Points:** This value determines how fast correlation is performed and how much processor time is available for other uses. The lower the number the faster correlation will run, but other programs that may be running will run slower. If no other processes are running, then this value should be set to one. This will allow the correlation to proceed at maximum speed.
- **Partials Zero?:** The program may correlate displacements with the assumption that all partials are zero. If there is not much strain or rotation, there is dominating rigid body translation, then this is a good assumption and will speed processing. Set this value to **Y** if all partials may be assumed zero. However, more accurate results will almost always be given if partials are allowed to be non-zero. Any

unintentional rotation or strain will thus be accounted for as the program calculates estimated values for displacement gradients. Set this value to N if all partials may NOT be assumed zero.

4.3 Entering Settings Data

The Settings Data window is shown in **Figure 10**. Enter values into any of the Settings data boxes by using the mouse to move the cursor into the desired box, clicking once, and then editing the value. The standard Windows editing keystrokes will work including Backspace and Delete.

Settings for correlation		
<input type="text" value="20"/>	Subset Size	
<input type="text" value="100"/>	First Row	<input type="button" value="Save"/>
<input type="text" value="400"/>	Last Row	
<input type="text" value="20"/>	Row Step Size	
<input type="text" value="100"/>	First Column	<input type="button" value="Use"/>
<input type="text" value="400"/>	Last Column	
<input type="text" value="20"/>	Column Step Size	
<input type="text" value="R"/>	Rows or Column	<input type="button" value="Cancel"/>
<input type="text" value="0"/>	Initial V Disp.	<input type="text" value="0.0"/> PuPx
<input type="text" value="0"/>	Initial U Disp.	<input type="text" value="0.0"/> PvPx
<input type="text" value="1"/>	Time Between Points	<input type="text" value="0.0"/> PuPy
<input type="text" value="Y"/>	Partials Zero?	<input type="text" value="0.0"/> PvPy

Figure 10. Settings Data Window

Once all values are set, the user has three choices to end and return to the main window. The choices are **SAVE**, **USE**, and **CANCEL**. If the **SAVE** option is chosen, then the values will be saved to the disk and when future copies of correlation are run, they will be used as default. If **USE** is selected, then the values will only be used for the current correlation and not in future uses. **CANCEL** will disregard any changes and use the values that were reported when Settings was first chosen. Select one of these three options by clicking once on the corresponding button.

4.4 Data Output File

When correlation is run the displacements are displayed on the screen and are also saved in a text file which is specified when **Go** is selected. Each point's correlation data is stored on a single line. The first value is the **Row** number and the

second value is the **Column** number of the point's location in the image as measured in pixels. The third and fourth values are the **U** and **V Displacements**, respectively. The **Correlation Factor** is stored in the fifth spot. The lower the **Correlation Factor** value the better the match between subsets. If the **Newton Raphson** method was used there will be four additional numbers, which are the displacement partials. In order, the file will contain:

$$X, Y, U, V, CF, \partial U/\partial x, \partial U/\partial y, \partial V/\partial x, \partial V/\partial y,$$

where **CF** is the Correlation Factor at each point.

4.5 Image Correlation Technique

The program has the ability to use several techniques for correlation. The Coarse-Fine Search method is more stable and less sensitive to image quality. It is only capable of obtaining **U** and **V** displacements. This method does not work if there is a significant amount of rotation of the object. Coarse Fine Search is the method that has seen the widest use. The Coarse Fine search method basically will try all possible **U** and **V** combinations, within a predetermined range, to find the best match. Because there are no displacement gradient terms, the match will deteriorate when large gradients are present. It has been found that if large amounts of rotation are not present, then the method works quite satisfactorily.

The Newton-Raphson method solves a set of nonlinear equations to determine the displacements and displacement gradients. This technique is newer and is gaining wider acceptance although it does require higher quality random patterns than the Coarse-Fine search method. The displacement gradients obtained with this technique may have a large error and are correct only if several are averaged together to smooth computational noise. The larger the subset size the more reliable and consistent the values will be. Again, it is the job of the program user to interpret the numbers obtained to determine if they are useful.

For more information, refer to:

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- Bruck, H. A., McNeill, S. R., Sutton, M. A., & Peters, W. H., Digital image correlation using Newton-Raphson method of partial differential correction, *Experimental Mechanics*, Sept. 1989, pp. 267.
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5. VIC Example

5.1 Example Files

Example images and outputs were included when the VIC system was installed, and can be found in C:\VIC\EXAMPLE. This example guides the user step by step through the program analyzing the images provided. Example output data files are included as a standard for comparison of the user's results. The names and contents of the example files are listed below.

Undeformed Image File	UND.IMG
Deformed Image File	DEF.IMG
Output Data File	VICEX.DAT

The example images are SRM 480's (480 pixels x 512 pixels). The images were taken of an applied pattern on a double edge crack aluminum specimen under tension. Between the two images, crack growth and opening has occurred.

5.2 Beginning the Example

1. Start the VIC application by double clicking on the VIC icon in the appropriate Windows Program Manager window.
2. Select the SRM's 480's **Image Type**.
3. Display the undeformed image.
4. Start a second VIC application by double clicking on the VIC icon in the appropriate Windows Program Manager window.
5. Display the deformed image in the new VIC window.
6. **Resize** and move the two VIC windows so that at least the upper left corner of each is visible. VIC windows may be moved by positioning the cursor on the title bar, pressing and holding the mouse button, moving the mouse to drag the window to the desired position, then releasing the mouse button. VIC windows may be resized by positioning the cursor on one of the window's borders where the cursor will change to a set of opposite pointing arrows. Press and hold the mouse button here while moving the border to the desired position, then release the mouse button.
7. Determine appropriate **Subset Size**. When the cursor is moved inside the displayed image, the row (X) and column (Y) of the cursor position will appear in the

text box above the image. Chose a subset size which will contain several distinct dark and light regions. For this example, use 20.

8. Determine values for First Row and First Column. These will give the coordinates for the center of the first subset to be correlated, and subsequent subsets will traverse this row and this column. A point being correlated uses pixels equal in number to 1/2 subset size above, below, left, and right of that point. Do not chose First Row and First Column values less than 1/2 subset size or the program will attempt to correlate pixels which are not on the image and will become unstable. For this example, First Row and First Column must be at least 10.

Also, if the physical boundaries of an applied speckle pattern are visible in the image, then First Row and First Column must be given values great enough that subset pixels do not run off of the pattern onto the un-patterned specimen surface. First Row must be at least the row which is farthest from the top edge of the image and lies on the upper boundary of the applied pattern, plus 1/2 subset size. First Column must be at least the column which is the farthest from the left edge of the image and lies on the left boundary of the applied pattern.

In the case of this example, the cracks at the sides of the deformed image break the applied pattern. Thus, First Column must be at least the value at the tip of the left crack, which is about 120, plus 1/2 subset size, which is 10. The First Column must be at least $120 + 10 = 130$. The top edge of the image does not require any continuity considerations for First Row.

These guidelines are for minimum values. Since deformation has occurred between the two images, subset pixels which exist in the undeformed image may not be found in the deformed image. For this example, use First Row = 30, First Column = 150.

9. Determine values for Last Row and Last Column. If the images are too large to display with the graphics mode in use, adjust the slide bars along the right and bottom edges of the VIC window to view the lower right corner of the image. Last Row and Last Column must be selected similarly to First Row and First Column. Last Row must be at most the row which is the farthest from the bottom edge of the image and lies on the lower boundary of the applied pattern, minus 1/2 subset size. Last Column must be at most the column which is the farthest from the right edge of the image and lies on the right boundary of the applied pattern, minus 1/2 subset size. Again these are minimum values.

For this example, the applied pattern extends without interruption beyond the lower edge of the image. Thus, Last Row must be at most $480 - 10 = 470$. The crack at the right side of the deformed image breaks the applied pattern. Thus, Last Column must be at most the value at the tip of the right crack, which is about 400, minus 1/2 subset size, which is 10. The Last Column must be at most $400 - 10 = 390$. To allow for deformation and simplify arithmetic, use Last Row = 430 and Last Column = 370.

10. Determine Row Step Size and Column Step Size. Chose values which are sufficiently small that they will provide enough data points to reflect the displacement of the full field. Choosing values which are too small will increase processing time

quadratically and will not significantly effect the accuracy of results. Typically, values are chosen such that the grid of points correlated will contain about 15 to 30 subsets in each direction. If a certain number of subsets is desired in each direction, then the step sizes may be determined from the following equations:

Row Step Size = (Last Row - First Row) / number of subsets in X direction,

Column Step Size = (Last Column - First Column) / number of subsets in Y direction.

For this example, a uniform spacing will be used rather than a specific number of subsets. Use Row Step Size = 20 and Column Step Size = 20.

11. Determine initial guess displacements. Locate an easily recognizable feature near the First Row and First Column on the undeformed image. Make sure that this feature is also visible on the deformed image. Record the undeformed coordinates of that feature.

Note: This example demonstrates the need for high contrast in images. The brightness of your monitor may need to be adjusted to locate pattern features.

Locate that same feature on the deformed image. Record the deformed coordinates. Calculate the initial guess displacements according to the following equations:

$$U_i = \text{Deformed Row} - \text{Undeformed Row} = X_D - X_U,$$

$$V_i = \text{Deformed Column} - \text{Undeformed Column} = Y_D - Y_U.$$

For this example, locate a point in the VIC window which is displaying the undeformed image. The coordinates of a suitable point are $(X_U, Y_U) = (51, 126)$. Locating the same point in the deformed image gives $(X_D, Y_D) = (70, 127)$. Thus, $U_i = 70 - 51 = 19$, and $V_i = 127 - 126 = 1$.

12. Select the Technique to be used. For this example, select Newton-Raphson Technique. This will allow a large number of points to be correlated quickly, and will result in values for displacement partial derivatives.

13. Select the Search Method to be used. For this example, select Grid. This results in data uniformly spaced throughout the correlation zone, and provides full-field displacements.

14. Select the Correlation Measure to be used. For this example, select Least Squares.

15. Select Settings. Enter the Settings Values determined in steps 1-11. Also, select values for Rows or Columns, Time Between Points, and Partial Zero?.

The value for Rows or Columns is arbitrary. For this example, enter r or R for Rows. Since this example only requires one correlation, use Time Between Points = 1. For this example, set Partial Zero? = n or N.

5.3 Correlating Example Images

1. Select Go from the Image Correlation Menu. When prompted, enter the filenames indicated above for the undeformed and deformed images, but DO NOT enter the output data filename indicated above. Enter a filename which does not appear in the directory window, and use the extension .DAT .

2. After reading the images and calculating preliminary values, the program will begin correlation the images. A red square will mark each subset as it is being correlated. The text box will report the displacement and partial values being used, and the correlation factor associated with each combination of values. Watch these correlation factors. If the correlation factor becomes very large, then the program has encountered an instability due to a poor initial guess, a physical discontinuity in the specimen, a poor or broken pattern, etc. If necessary, stop the correlation, close the application, and start over.

If the program finds that large changes in the displacement and partial values cause very small changes in a large correlation factor, then the Newton-Raphson routine may suspend itself, invoke the Coarse-Fine Search routine, and use its results for that point as an initial guess for continued Newton-Raphson processing on the same point.

3. **Be Patient.** Each subset has $20 \times 20 = 400$ pixels. Each of those 400 pixels may have one of 256 possible gray levels. Each of those 400 pixels with one of 256 possible gray levels is allowed an infinite range of planar motion. That is, VIC juggles 400 pixels at a time, remembering which of 256 gray levels belongs to each pixel, and determines from an infinite range of values just how far the group of pixels has moved up or down and left or right, how much it has stretched or compressed top to bottom and side to side, how much it has rotated, and how far out of square it has gotten. Those are a lot of numbers to crunch, and crunching numbers takes time, so crunching a lot of numbers takes a lot of time.

5.4 Example Results

Select Display Colors. For each choice (U, V, Partial U with x, etc.) select the data output file name used with the example correlation. Your results will be displayed as a color field. The position of each pixel in this field is the same as that in the undeformed image. The color of each pixel indicates the value of the chosen result. A scale for interpreting these colors appears above the color field.

Select Display Colors again, using the filename C:\VIC\EXAMPLE\VICEX.DAT. Standard results will be displayed, which should be the same as those acquired running the VIC example. If there are differences, then the procedure was not followed exactly. Try the VIC example again until the same results are obtained. If the standard results cannot be duplicated contact Steve McNeill at (803) 777-3407.